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DYNAMICAL CLIMATOLOGY TECHNICAL NOTE NO. 47

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Simulation of the Diurnal Cycle of Outgoing Longwave Radiation with an Atmospheric GCM

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ABSTRACT

Results are presented from an integration of the U. K. Meteorological Office 11-Layer Atmospheric General Circulation Model, with emphasis on the simulation of the diurnal cycle of the outgoing longwave radiation. The model reproduces many of the features which have been noted from observational studies with satellite data. It is argued that such comparisons between models and observations have considerable potential not only for validating the cloud and other parameterization schemes used in models but also for understanding the origin of the observed variations.

1. Introduction

Observations of the Earth's Radiation Budget (ERB) from satellite platforms have proved to be invaluable for studies of climate and for validating climate models (Hartmann et al. 1986). These data show directly the horizontal distribution of radiative heating which is the energy source for the earth's climate system. In addition, because that heating is strongly influenced by the cloud cover, the data also contain information on the distribution and radiative properties of clouds. These observations therefore provide one of the most important sources of validation for assessing the schemes used to predict cloud fields in Atmospheric General Circulation Models (AGCMs). Such assessments have traditionally concentrated on mean climatologies derived from several years of data, but the observed variations on a wide range of time-scales could also be used. In particular, several recent studies have demonstrated that in many regions there are substantial systematic variations in the ERB and cloud fields in response to the diurnal cycle of solar heating. Data from the GOES (Minnis and Harrison 1984) and METEOSAT (Duvel and Kandel 1985) geostationary satellites and from various polar orbiters (Hartmann and Recker 1986) have been analysed. In this note, results from an AGCM are used to demonstrate that such data have considerable potential for further validating the cloud and other parameterization schemes employed in models.

2. Model and integration

The U.K. Meteorological Office 11-Layer Model is a finite difference AGCM which is formulated in sigma coordinates on a regular latitude/longitude grid. An early version was used to study the climate of the Saharan region by Cunnington and Rowntree (1986), who also described the convection scheme. More recently, studies have been made of the model's response to sea surface temperature anomalies associated with El Niño (Palmer and Mansfield 1986) and to envelope orography and a parameterization of orographic gravity wave drag (Palmer et al. 1986, Slingo and Pearson 1987). Basic details of the

model are given by Slingo and Pearson (1987) and the development of the longwave part of the radiation scheme is described by Slingo and Wilderspin (1986). A comprehensive handbook of the model is also available (Slingo 1985). The model has since been modified to improve the quality of the cloud and ERB simulations, through various changes including revised convection, boundary layer and cloud prediction schemes . A paper describing those changes and presenting results from a control simulation with the new model is in preparation. The results shown here are from a development version which differs only in minor respects from the new model.

For most applications the model is integrated with a resolution of 2.5° in latitude by 3.75° in longitude. The model predicts the fractional coverage both by layer clouds (which occupy a single model layer) and by a convective cloud tower (which may be any number of model layers deep). The layer cloud amounts are calculated by a quadratic dependence on the environmental relative humidity, rising from zero at the threshold relative humidity (typically 85 per cent) to full cover at saturation. The convective cloud amount is proportional to the vertically-integrated mass of condensed water calculated in the penetrative convection scheme and the cloud base and top required in the radiation computations are determined by the layers in which the moist convection begins and ends. The radiation and cloud prediction schemes are called every 3 hours of model time in order to resolve the diurnal cycle.

The model was integrated through a complete annual cycle using initial conditions taken from the end of June of a previous integration. The results shown here are meaned over the month of January.

3. Results

The mean outgoing longwave flux from the model for the month of January is compared with Nimbus 7 data (Jacobowitz et al. 1984) for January 1980 in Figure 1. The model reproduces the major features in the observed distribution, notably the minima in the tropical regions due to deep convective clouds over South America, southern Africa,

Indonesia, the Inter-Tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). There are maxima in the sub-tropics where the cloud is much lower . The values also decrease realistically towards the poles.

The good agreement between the observed and modelled mean outgoing longwave flux indicates that the cloud prediction scheme is working satisfactorily, at least as regards the cloud associated with deep convection. However, as noted in the introduction, additional information can be gleaned from the simulation of the diurnal cycle, as will now be discussed.

Satellite data on the diurnal cycle of the outgoing longwave flux were presented by Minnis and Harrison (1984) and Hartmann and Recker (1986) in the form of maps in which the phase of the diurnal cycle at each grid point was represented by the direction of an arrow on an imaginary 24 - hour clock, based on local time. The amplitude and phase were obtained by an harmonic analysis of the data. A slightly different method is employed here, which is explained in Figure 2. The advantage of this representation is that it does not assume that the form of the diurnal variation is sinusoidal. A coherent, but non-sinusoidal, diurnal variation appears as a bent arrow, while a sinusoidal variation leads to a straight arrow. As will be seen, over much of the globe the model's diurnal variation is not sinusoidal and it would be interesting to see the satellite data analysed in the same way to establish whether this behaviour is realistic.

The mean diurnal cycle in the outgoing longwave flux for January from the model is shown in Figures 3(a) and 4(a), using the notation illustrated in Figure 2. In addition, Figures 3(b) and 4(b) show the diurnal variation of the clear-sky contribution to the flux. Archiving the clear-sky flux separately makes it possible to isolate the cloud radiative forcing of the general circulation, by subtracting this component from the total flux (Ramanathan 1986, Hartmann et al. 1986). For the present study, the diurnal variation in the clear-sky flux is itself of considerable interest because it is dominated by the diurnal variation in the surface temperature. Over the oceans, the use of prescribed sea surface temperatures leads to a very weak diurnal cycle in the clear-sky flux as this responds only to changes in atmospheric temperature and moisture content. The variation is also weak over land at high latitudes because the surface insolation is small. However, elsewhere

over land there is a substantial diurnal variation due to changes in the land surface temperature. The amplitude of the variation is greatest in those regions where there is little cloud cover and the soil moisture content (which is a prognostic variable of the model) is lowest, because here the evaporation is lowest and so the surface temperature responds most strongly to changes in insolation. This may be seen by comparing the contours of the amplitude on Figures 3(b) and 4(b) with the mean flux shown in Figure 1(a). At low latitudes, where the precipitation is mainly convective, there is a strong correlation between high soil moisture content and high precipitation and hence with low outgoing longwave flux. The diurnal variation is thus strongest over the Sahara desert (where it exceeds 40 W m^{-2} over large areas) and over the deserts of southern Africa and south Australia . Over North and South America the pattern is in reasonable agreement with the same diagnostic derived by Minnis and Harrison (1984) from GOES data (Their Figure 14 from Part III), with a minimum in the Amazon basin and maxima over the Andes and Rockies. For most of the areas where the diurnal variations are significant, the minimum occurs in the early morning and the maximum in the late afternoon, as one would expect from variations in the surface temperature.

Variations in the cloud cover lead to greater complexity in the diurnal cycle of the total longwave flux (Figures 3(a) and 4(a)) compared with the clear-sky component. Over land, the clear sky signature can still be seen in areas where the cloud amounts are small, notably the Sahara. Elsewhere, the patterns are much more complicated. Over South America there are maxima in excess of 40 W m^{-2} associated with changes in the convection in the Amazon basin and North-East Brazil, as was also found by Minnis and Harrison (1984, Part III, their Figure 22). Their data show a maximum in the outgoing longwave flux at around local noon (their Figure 17), although Hartmann and Recker show earlier maxima in this season (their Figure 1(a)). In the model there are less coherent variations with maxima at various local times.

Of particular interest in Figures 3(a) and 4(a) are the oceanic areas with coherent diurnal variations in excess of 20 W m^{-2}. Comparison with the clear-sky maps shows that these variations are almost entirely due to changes in the cloud cover, as was also found in the observations. The largest variations are in the Indian Ocean, Indonesia and

in the Pacific ITCZ extending from 150^0 E across the dateline to 150^0 W. Similar patterns are shown by Hartmann and Recker (1986). In the Pacific ITCZ there is a maximum in the outgoing longwave flux around noon and a minimum at night. This is in broad agreement with the phase of the diurnal cycle found by Hartmann and Recker. It suggests that the high cloud cover is a maximum during the night, although both Albright et al. (1985) and Hartmann and Recker (1986) argue that the cloudiness variations are much more complicated then this simple picture, with changes in cloud cover at different levels producing partly compensating changes in the outgoing longwave flux.

Both Minnis and Harrison (1984) and Hartmann and Recker (1986) show that there are significant diurnal variations in the low cloud cover and outgoing longwave flux in the stratocumulus regimes of the South-East Pacific and Atlantic oceans. These variations are probably forced by the diurnal cycle in the absorption of solar radiation within the cloud (Turton and Nicholls 1986). While Figure 3(a) shows some variations in these areas, they are primarily due to changes in higher cloud layers and there is little evidence for coherent diurnal variations in those regions where the model predicts substantial low cloud cover unobscured by higher cloud (i.e. close to the coasts of South America and South Africa between about 15^0 S and 30^0 S). It is not yet known whether this is due to a failure to represent the cloud cover variations themselves or to the cloud top temperature being too close to the sea surface temperature for a signal to appear in the outgoing longwave flux. Further work is planned to study this aspect of the simulations, given the importance of these clouds in the radiation budget.

4. Discussion

The purpose of this note is to demonstrate the value of comparisons between model simulations and satellite observations of the diurnal cycle in the earth's radiation budget and to encourage further such studies. By separating the clear-sky contribution from the total outgoing longwave flux it is possible to study the diurnal cycle in the land surface temperature, which may yield useful information on the realism of the methods used to

represent land surface processes in models. Additionally, since the diurnal cycle in the outgoing longwave flux is strongly influenced by changes in the cloud cover, it should also be possible to assess the cloud parameterization, particularly in regions where the cloud is convective in origin. Over the oceans, the observed diurnal variations in the ITCZ are presumably the result of subtle interactions between radiative and convective processes and there may be information here which would be of value in developing a closer link between the model parameterizations for these processes. The significant observed diurnal variation in the areas of marine sub-tropical stratocumulus may indicate the need for such a link between the radiative, turbulence and condensation parameterizations (Turton and Nicholls 1986). It should also be noted that failure to include the diurnal cycle or to resolve it adequately can lead to a degradation in the quality of model simulations (Randall et al. 1985; Wilson and Mitchell 1986).

The successful simulation of the observed diurnal cycle would thus enhance considerably the credibility of a model for climate studies. Such a model would also be a powerful tool for understanding the processes which control the observed diurnal variations. Models used for numerical weather prediction could also benefit from such comparisons, particularly if the evolution of the modelled diurnal cycle during a forecast could be compared with satellite data for the same time period. One advantage of this type of study is that it is not necessary to employ long integrations of a model, the averaging period used here being only 30 days, although it would be interesting to determine whether the character of the modelled diurnal cycle varies with time of year or synoptic conditions.

This preliminary study has demonstrated that the model shows some success in reproducing the observed diurnal variations. A more detailed investigation is planned with extensive diagnostics, particularly of the cloudiness and related fields. Clear and total outgoing longwave fluxes and their diurnal variation are also being obtained as part of ERBE (Barkstrom and Smith 1986), so this investigation should make a timely contribution to this fascinating area of research.

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FIGURE CAPTIONS

Figure 1 Mean outgoing longwave flux in W m^{-2} for January from (a) the model and (b) Nimbus 7 Narrow Field Of View data for 1980. The contour interval is 25 W m^{-2} with shading below 225 W m^{-2}.

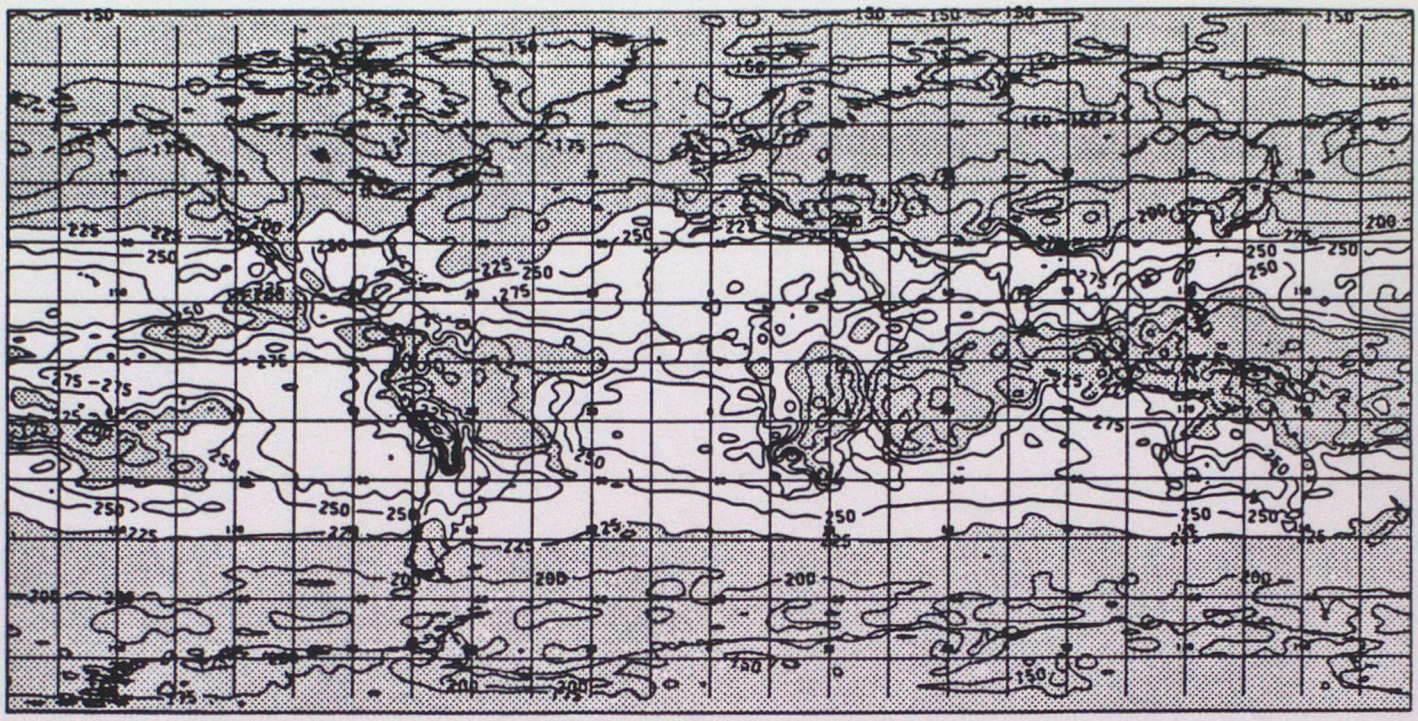
Figure 2 The graph at the top illustrates schematically the variation of the outgoing longwave flux through the day at a model grid-point, with a minimum at 0730 local time and a maximum at 1630 local time. This coherent, but non-sinusoidal, behaviour may be represented by an arrow on an imaginary 24-hour clock. The tail of the arrow points at the local time of the minimum and the head points at the local time of the maximum. Thus the variation shown on the graph is represented as in the lower diagram.

Figure 3 (a) Mean diurnal variation of the total outgoing longwave flux from the model for January, using the representation explained in Figure 2. The length of the arrow is proportional to the amplitude of the variation up to 30 W m^{-2} and is constant for larger variations. In addition, contours of the amplitude are shown dotted, with a contour interval of 20 W m^{-2}. No arrows are plotted if the amplitude is less than 2 W m^{-2}. The map is for the area 45^0 N to 45^0 S and 120^0 W to 60^0 E . Latitude and longitude lines are plotted every 15^0.

(b) Same as (a) but for the clear-sky contribution.

Figure 4 Same as Figure 3 but for the other hemisphere.

(a) Model



(b) Nimbus 7

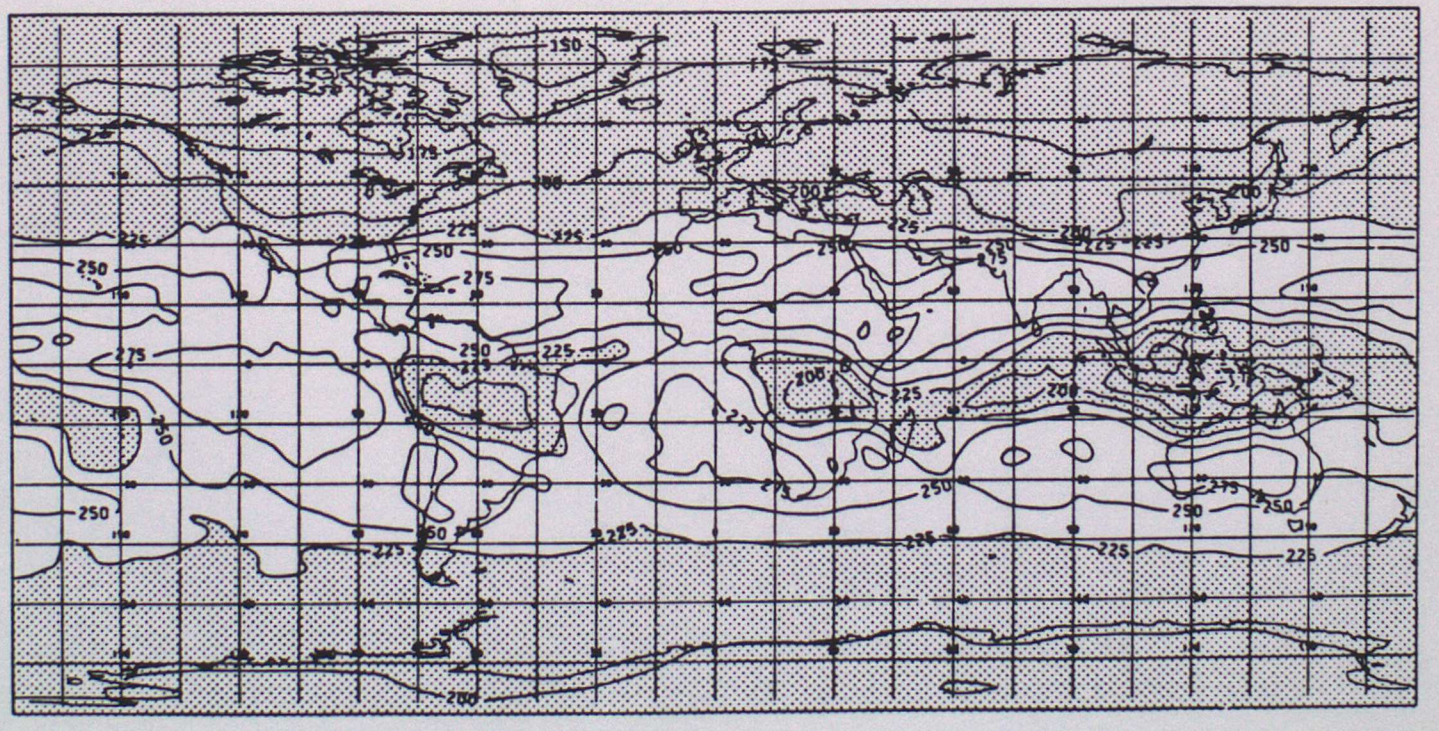
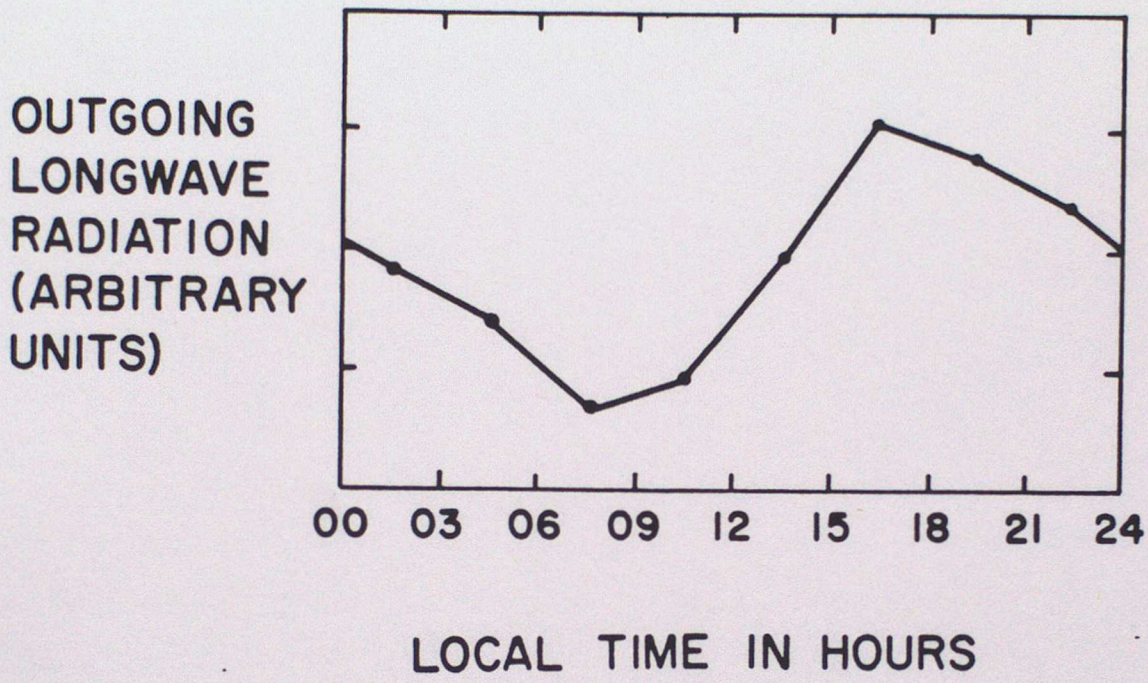


Fig. 1


OUTGOING
LONGWAVE
RADIATION
(ARBITRARY
UNITS)
00
03
06
09
12
15
18
21
24
LOCAL TIME IN HOURS

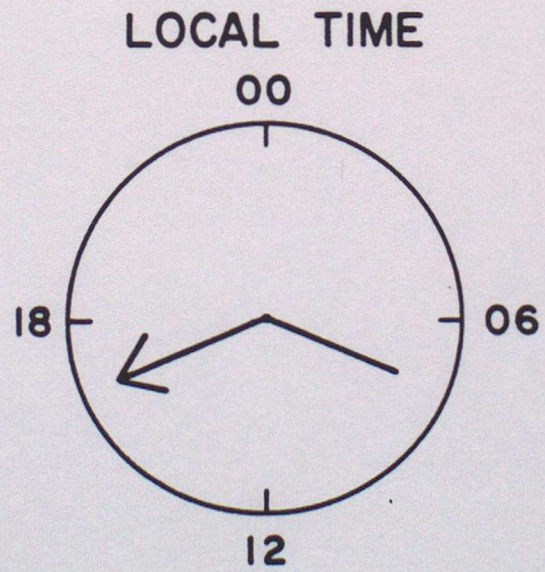
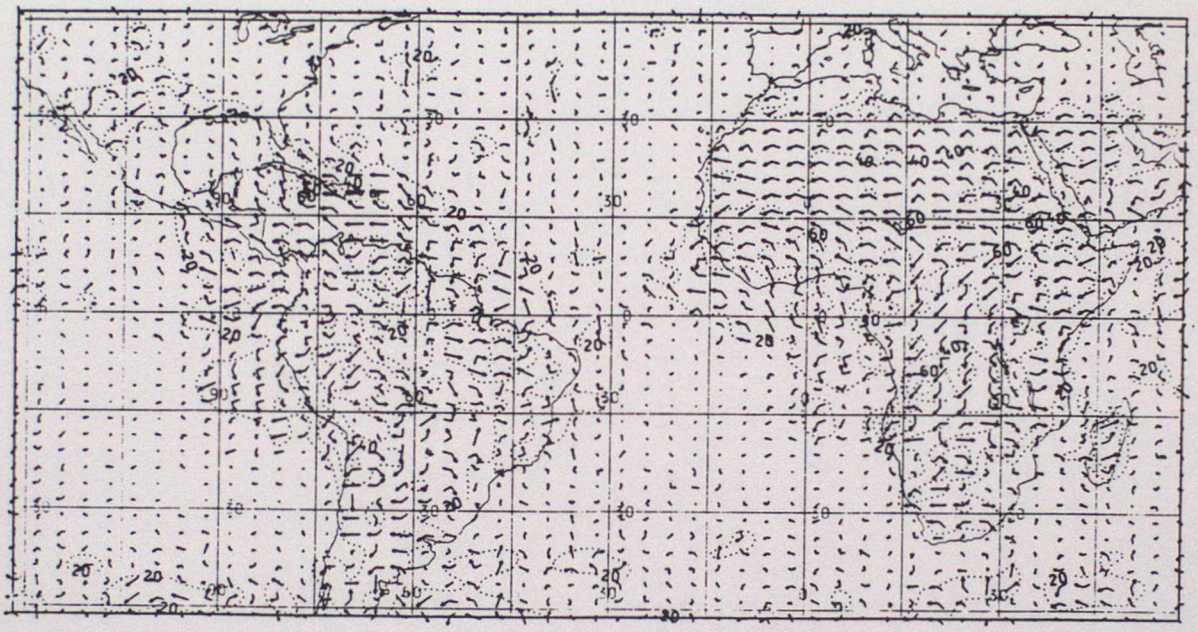

LOCAL TIME
00
18
06
12

Fig. 2

(a) Total



(b) Clear-Sky

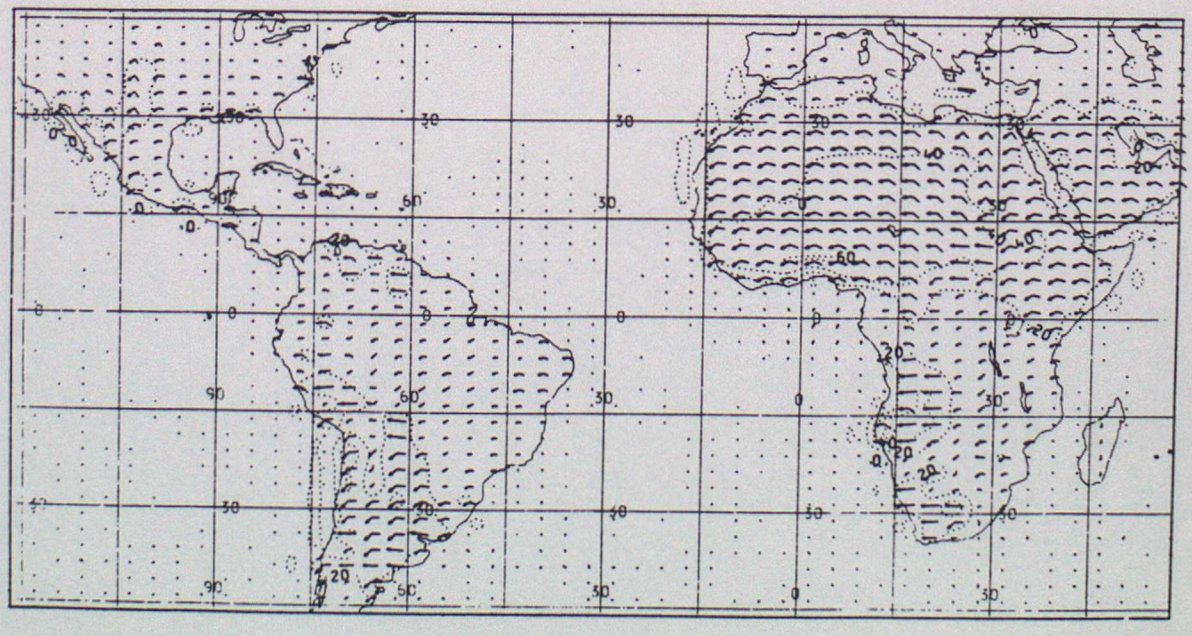
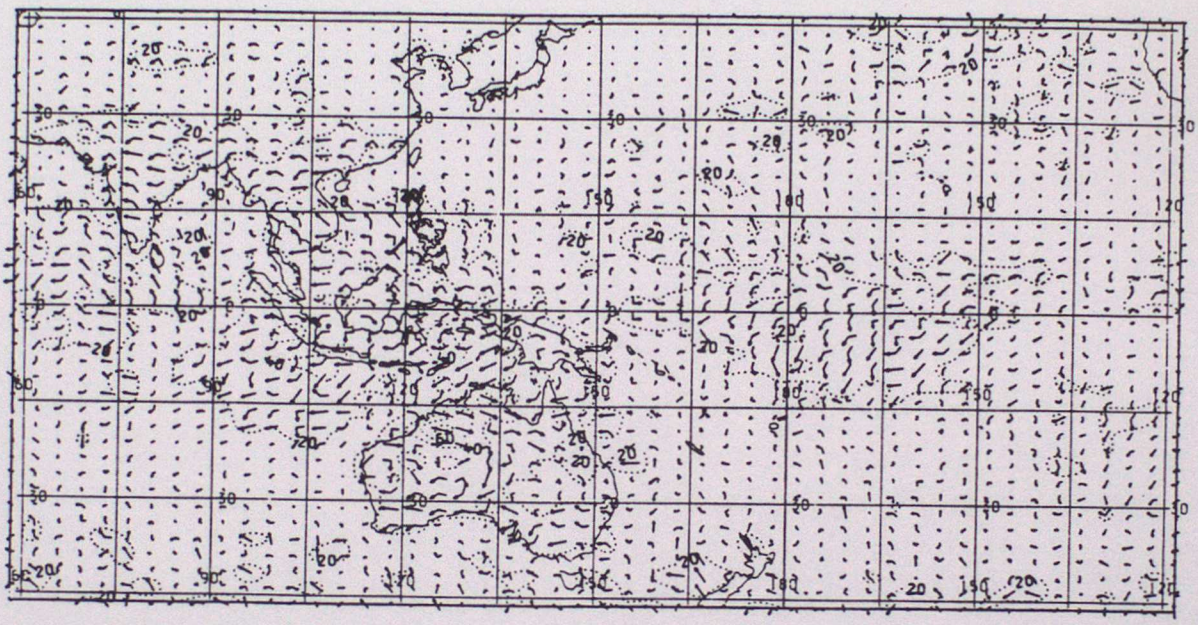


Fig. 3

(a) Total



(b) Clear-Sky

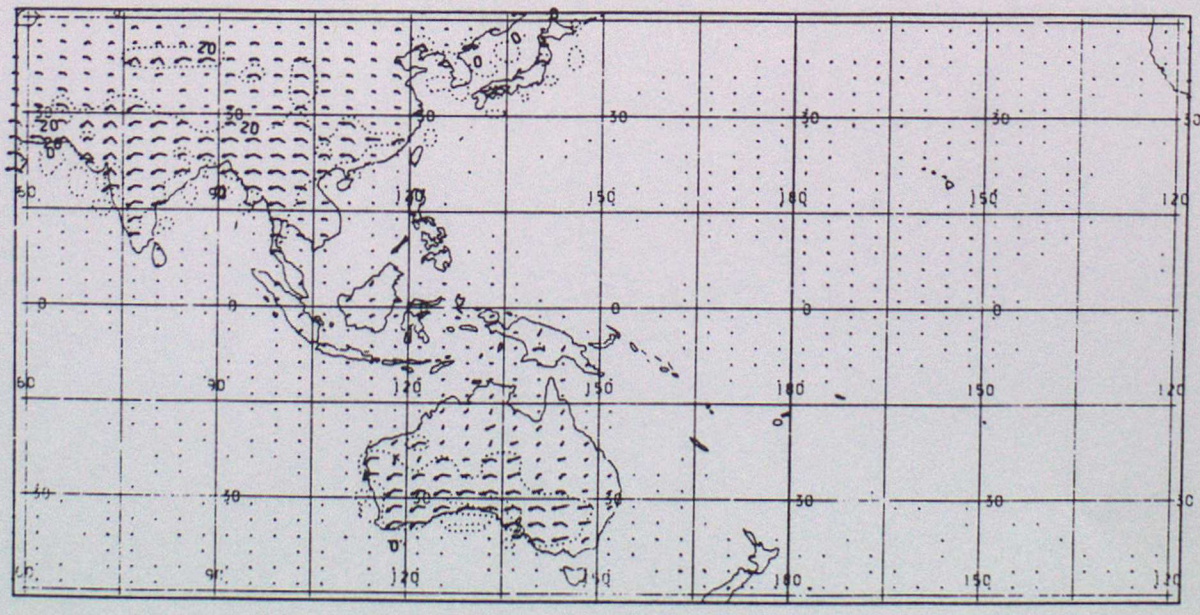


Fig. 4

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